GMAO RESEARCH BRIEF
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Southern Polar Ozone in MERRA-2

Krzysztof Wargan

SUMMARY

MERRA-2 provides a good representation of the year-to-year variations and the long-term changes in total ozone column over Antarctica for the entire data record, beginning in 1980. When MLS data are introduced into MERRA-2 in 2004, agreement with independent data improves compared to earlier years when the SBUV observations were assimilated.

BACKGROUND

Stratospheric ozone is a key component of the Earth's system in that it shields the biosphere from harmful ultraviolet radiation and largely determines the thermal structure of the middle atmosphere. In agreement with the results of Molina and Rowland (1974), anthropogenic emissions of chlorine compounds into the atmosphere have led to a decline in global stratospheric ozone observed since the 1980s. The presence of these substances in the stratosphere is almost entirely a result of past industrial emissions of chlorofluorocarbons (CFCs) before the international agreement banning their production (Montreal Protocol of 1986) went into effect. The stratospheric ozone layer is expected to return to its pre-1980 values within a few decades (WMO 2014).

A correct representation of the southernmost total ozone in atmospheric reanalyses is important for climate studies. In particular, it helps to monitor long-term trends in the stratospheric ozone layer. It is also challenging, as most of historical ozone data are derived from satellite measurements of scattered solar radiation, which are not available during polar night. NASA's Modern Era Retrospective Analysis for Research and Applications – 2 (MERRA-2) is the GMAO's latest atmospheric reanalysis covering the period of 1980 to present (Bosilovich *et al.* 2015). The reanalysis combines observations from satellites and conventional data, such as radiosonde and aircraft measurements, with simulations performed by an atmospheric general circulation model. Both the model and the observing system used in MERRA-2 have been substantially upgraded since the previous reanalysis, MERRA. Since 1979, the ozone data in MERRA were observations from the Solar Backscatter Ultra Violet Radiometers (SBUV) flown on various NOAA satellites. MERRA-2 uses SBUV only until October 2004 and then switches to observations from the Ozone Monitoring Instrument (OMI) and stratospheric ozone profiles from the Microwave Limb Sounder (MLS). Unlike the other instruments, MLS has near-global day and night coverage. Both OMI and MLS are flown on NASA's Earth Observing System Aura satellite.

Antarctic Ozone Holes in MERRA-2

The most dramatic manifestation of the 20th century ozone depletion is the seasonal occurrence of 'ozone holes' over Antarctica. An ozone hole is a large region of the atmosphere, highly depleted of stratospheric ozone. The amount of atmospheric ozone varies both seasonally and spatially, but the typical values of vertically integrated overhead concentrations (the total column) oscillate around 290 Dobson units (DU), corresponding to 8×10^{18} ozone molecules per square centimeter. Under the ozone hole conditions, the total column falls to under 220 DU, sometimes reaching values close to 100 DU with concentrations in the lower stratosphere dropping down to almost zero. Ozone holes form over the southern high latitudes during the austral spring every year since the 1980s, due to a complex sequence of chemical reactions that take place on the surfaces of small particles and droplets of polar stratospheric clouds (PSCs), whereby active chlorine is released from its chemically inert reservoir species. The chlorine atoms then catalytically destroy ozone. Three key conditions for the ozone hole formation are 1) stratospheric temperatures low enough for PSCs to form, 2) strongly isolated air mass over the Antarctic, and 3) the presence of chlorine (and bromine) compounds in the stratosphere. The first two conditions are met during southern winter and spring over the

South Pole, where strong circumpolar circulation (the polar vortex) isolates extremely cold air from the middle latitudes. Antarctic ozone holes did not exist prior to 1980 and are expected to disappear within a few decades once the remaining chlorine compounds have been removed from the stratosphere by large-scale circulation.

The top portion of Figure 1 shows a map of the total ozone column (TOC) in the southern hemisphere averaged from MERRA-2 ozone fields between 20 September and 10 October of 2015 with the 220 DU ozone hole boundary depicted as a black contour. The bottom portion shows the ozone hole area as a function of time. Readily seen is an upward trend in the 1980s, consistent with the increase of anthropogenic chlorine in the stratosphere. The average area reaches a plateau in the 1990s modulated by year-to-year variations.

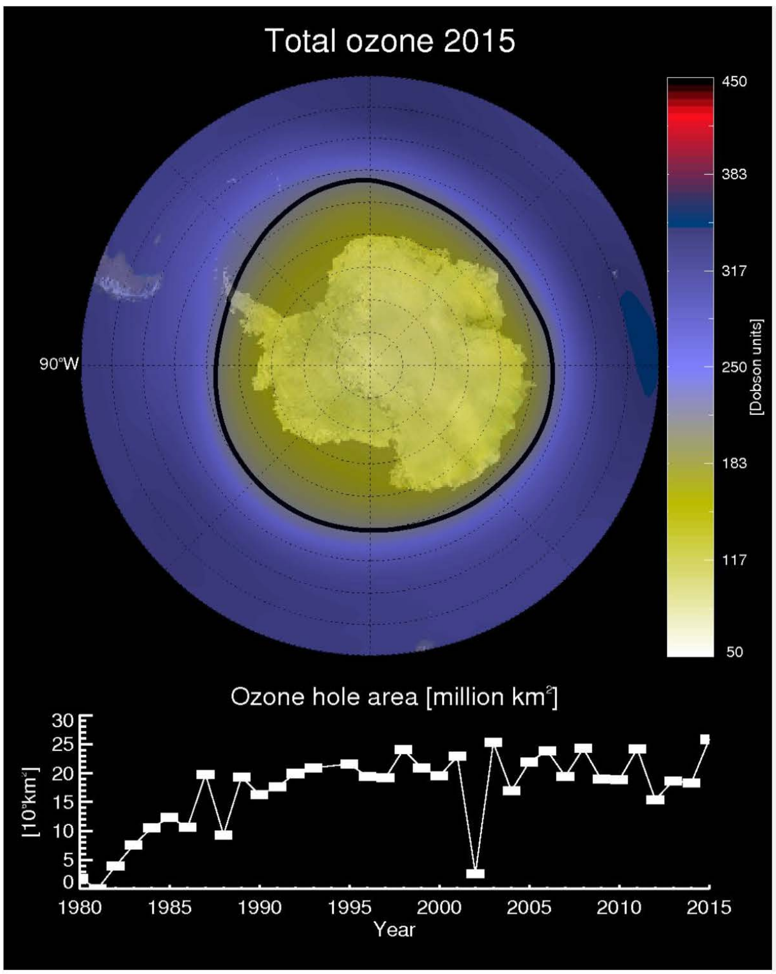

Figure 1.

Top of image: A map of total ozone column in the southern hemisphere averaged from MERRA-2 ozone fields between 20 September and 10 October 2015. The 220 DU mark (the boundary of the ozone hole) is shown as a thick black line.

Bottom of image: The time series of the ozone hole area between 1980 and 2015. The year 1994 is omitted due to insufficient data coverage in the southern hemisphere.

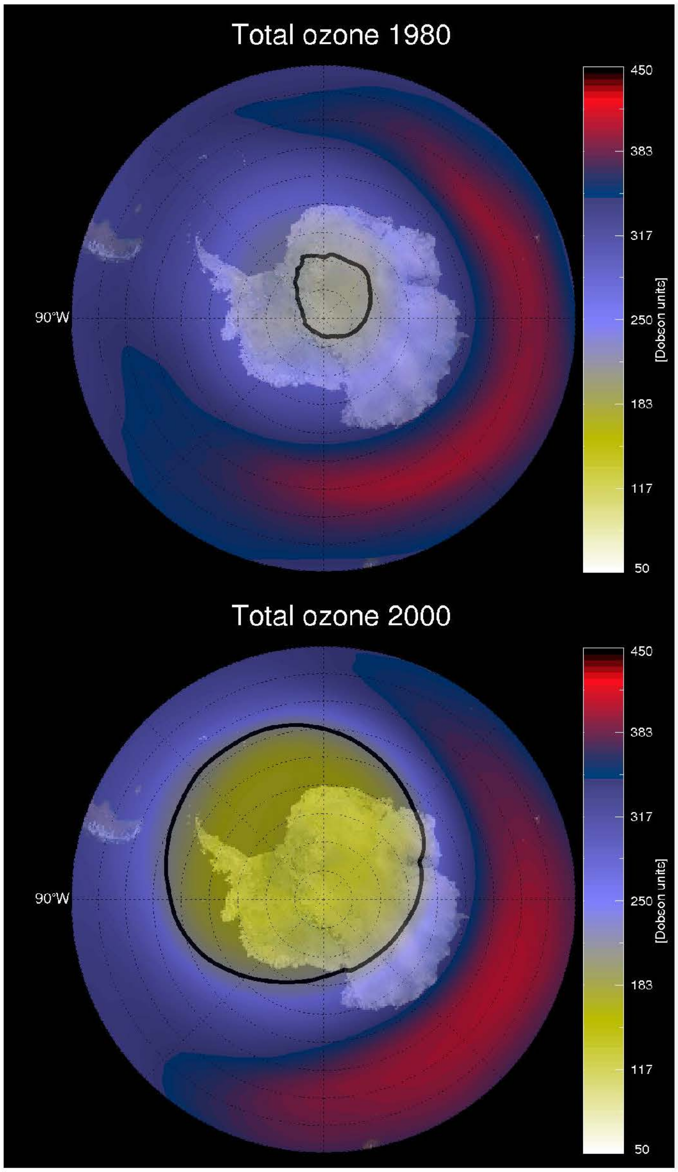

Figure 2.

Top of image: A map of total ozone column in the southern hemisphere averaged from MERRA-2 ozone fields between 20 September and 10 October 1980. The 220 DU mark (the boundary of the ozone hole) is shown as a thick black line. The lowest values are shown in yellow.

Bottom of image: The same as above but for the 2000 ozone hole.

A series of total ozone maps showing the MERRA-2 total ozone averaged over the southern hemisphere between 20 September and 10 October in years between 1980 and 2015 has been combined into an animation.

Figure 2 shows the MERRA-2 ozone holes in 1980 and 2000. During the intervening years, the average size of ozone holes increased from about 1,900,000 km^2 (zero in previous decades) to 20,000,000 km^2 and more. Interesting features seen in Figure 1 are the crescent-shaped patches of high ozone values over the Southern Ocean. These represent

what would be the seasonal ozone maxima in the southern hemisphere had they not been eroded by the extreme depletion within the ozone holes.

It is evident from the time series shown in Figure 1, that the size of ozone holes varies significantly from year to year. These variations, which are superimposed on decadal trends, are caused by interannual variability of stratospheric dynamics: cold (warm) stratospheric conditions lead to stronger (weaker) ozone depletion. For example, the very cold, austral spring of 2015 with a strong, relatively undisturbed stratospheric polar vortex produced an ozone hole exceptionally large in spatial extent (Figure 1).

By contrast, less ozone depletion is observed in years when the polar vortex is weak. As a side note, this is the reason why ozone holes generally do not form over the Arctic where the springtime stratosphere is warmer and dynamically more variable compared to the Antarctic. An extreme example is a very unusual, sudden stratospheric warming event that occurred in late September 2002, leading to an early disintegration of the polar vortex and a breakup of the ozone hole. The average ozone hole area between 20 September and 10 October 2002 was only about 2,600,000 km^2 (Figure 3) despite large concentrations of chlorine compounds in the stratosphere.

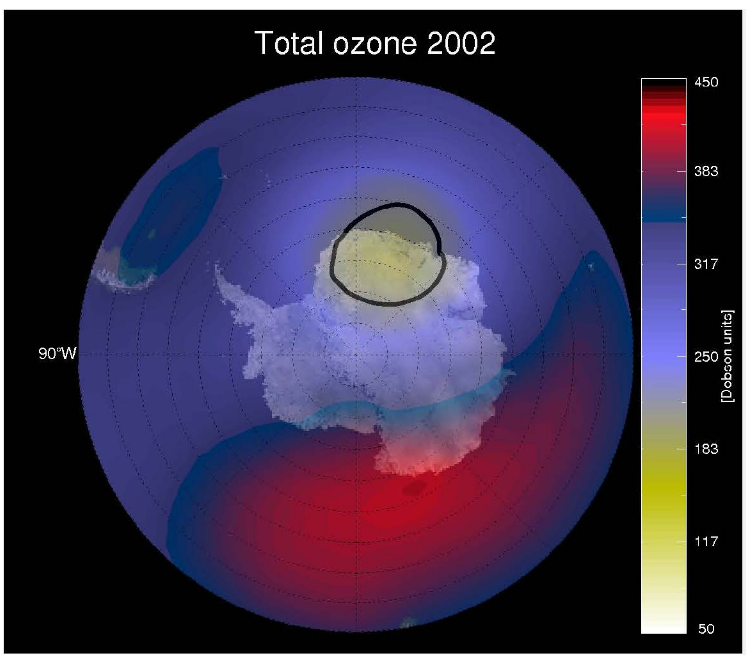

Figure 3.

As in Figure 2 but for the 2002 ozone hole (20 September – 10 October average). The extremely small ozone hole in that year was a consequence of a major sudden stratospheric warming event – the only one ever observed in the southern hemisphere.

The representation of ozone holes and their interannual variability in MERRA-2 is in agreement with independent analyses, e.g. ozonewatch.gsfc.nasa.gov.

Agreement with South Pole Ozonesondes

Figure 4 compares the TOC over the South Pole from MERRA and MERRA-2 with data derived from ozonesonde observations. Since ozonesonde measurements are not used in either reanalysis, they provide an independent data set for assessing the quality of the GMAO analysis. Both MERRA and MERRA-2 reproduce a realistic annual cycle of the South Pole ozone consistent with the ozonesonde data.

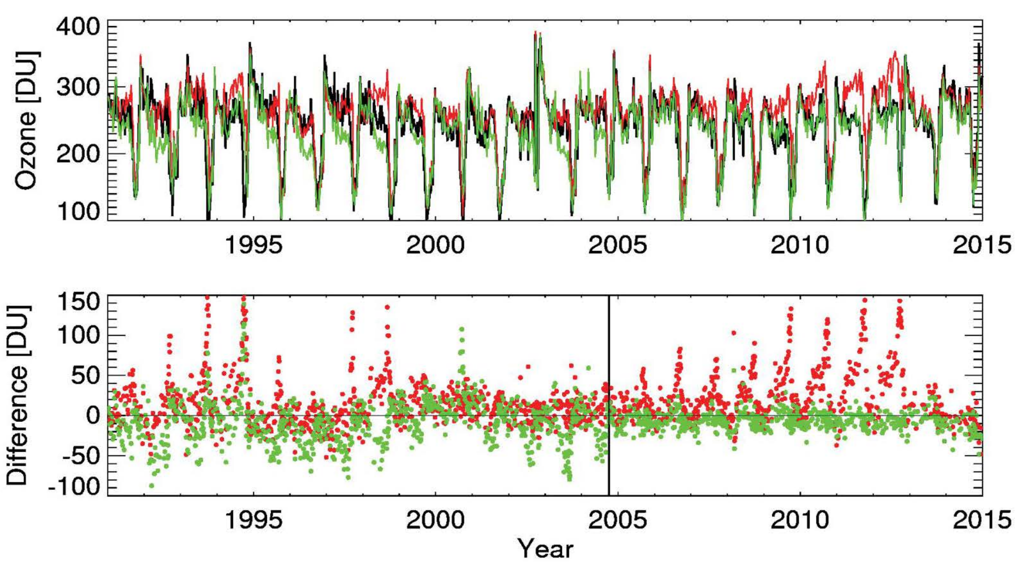

Figure 4. *Top panel:* Time series of South Pole ozone derived from ozonesondes (black), MERRA (red) and MERRA-2 (green). *Bottom panel:* the differences: MERRA minus ozonesondes (red) and MERRA-2 minus ozonesondes (green). The South Pole ozonesonde data were obtained through the NOAA Earth System Research Laboratory Global Monitoring Division *(www.esrl.noaa.gov/gmd/ozwv/ozsondes/spo.html)*

The ozonesonde-reanalysis statistics (Table 1) show that MERRA-2 is in closer agreement with the ozonesondes than MERRA throughout the period of comparison (1991 - 2014) and that it performs significantly better from the year 2004 onwards, when it assimilates stratospheric ozone observations from the

Microwave Limb Sounder with near-global coverage during both day and night. This is also seen in the statistics accumulated in Table 1. In particular, the standard deviation of the differences between MERRA-2 and ozonesondes drop from 28.23 DU to 11.1 DU between the periods of SBUV and MLS assimilation. However, we emphasize that also in the SBUV assimilation period (before 2004) the correlation between MERRA-2 and the total ozone derived from the sondes is high (0.88), indicative of the ability of the reanalysis to capture the variability of the total ozone column over the South Pole.

Analysis-sonde difference	14.03 DU -6.72 DU	26.56 DU -6.77
Analysis-sonde Correlation	0.87 0.88	0.80 0.98
Standard deviation of the Analysis-sonde differences	30.19 DU 28.23 DU	36.00 11.10

Table 1. Statistics of the South Pole Ozonesonde – Reanalysis Comparisons for MERRA (red) and MERRA-2 (green)

In summary, MERRA-2 provides a realistic representation of the total ozone column in the southern polar region throughout the entire period of reanalysis, including the interannual variability of the ozone holes in agreement with established science. Agreement with independent data improves during the period of 2004 to present when ozone observations from the MLS instrument are assimilated in the reanalysis.

References

Bosilovich M. and co-authors (2015): MERRA-2: Initial Evaluation of the Climate. Technical Report Series on Global Modeling and Data Assimilation, NASA/TM–2015-104606/Vol. 43.

Molina, M. J., & Rowland, F. S. (1974): Stratospheric Sink for Chlorofluoromethanes: Chlorine Atom-Catalysed Destruction of Ozone. *Nature*, *249* (28), 810-812.

World Meteorological Organization (WMO 2014): Scientific Assessment of Ozone Depletion: 2014. Global Ozone Research and Monitoring Project – Report no. 55.